CHARACTERISATION OF RADIO FREQUENCY INTERFERENCE FOR GNSS MARITIME APPLICATIONS

Andriy Konovaltsev(1), Emilio Pérez Marcos(1), Stefano Caizzone(1), Kazeem Yinusa(1), Michael Meurer(1)(2)

(1) Institute of Communications and Navigation, German Aerospace Centre (DLR)
Oberpfaffenhofen, Germany
Email:Andriy.Konovaltsev@dlr.de

(2) Chair of Navigation, RWTH Aachen University
Aachen, Germany

ABSTRACT

An international maritime measurement campaign on board of a large container ship was carried out in order to detect and record radio frequency interference events in the frequency bands allocated to open services of global satellite navigation systems. The measurement set-up consists of a conformal seven elements antenna array, a data recorder system and a multi-antenna navigation receiver prototype. In this paper, the system is briefly presented, together with the proposed detection and analysis methodology. An overview of the measurement results is given, including the characteristics of the most noticeable interference events.

INTRODUCTION

Global Navigation Satellite Systems (GNSS) such as American GPS and European Galileo have become the main technology to provide position and timing services worldwide. The increasing dependency on these services across many application fields has raised concerns about the vulnerability of GNSS. The navigation signals of GNSSs are typically received by the user antenna with a power as small as -154 dBW or less. This is the reason for the inherent susceptibility of the GNSS services to radio frequency interference (RFI). Unintentional and deliberate interference signals constitute a challenging problem in many Safety of Life applications and in Liability Critical applications, such as the use of GNSS in maritime domain. Several studies have demonstrated a high vulnerability of maritime navigation systems to deliberate GNSS interference, specifically jamming and spoofing attacks [1][2]. The development of adequate countermeasures is one of the topics addressed by the e-Navigation strategy launched by the International Maritime Organization (IMO) [3]. One of the proposed solutions is to reduce the vulnerability of the next generation of GNSS receivers by making use of additional navigation signals and frequency bands [4].

The development of adequate countermeasures against radio frequency interference, deliberate or unintentional, requires the knowledge about the several typical signal environments encountered by a shipborne GNSS receiver. Yet, most of the publicly available information regarding interference signals and corresponding impact on GNSS services focuses on airborne [5] or land-borne [6] receivers. Only little information is currently available about the signal situation in the maritime environment and mostly regarding some RFI events occurred in harbors [7][8]. In order to provide some more insight into the topic, the Institute of Communications and Navigation of the German Aerospace Center (DLR) conducted a worldwide maritime RFI measurement campaign on board of a large container ship. The measurement campaign took place between April 2017 and February 2018. The main objective of the campaign was to detect, observe and record radio frequency interference events in the GPS and Galileo Open Services frequency bands - L1/E1 and L5/E5a. Both L1 and L5 bands are strictly regulated, with L1 band being actually reserved only for radio navigation services, while L5 band allows coexistence of several radio systems. A multi-antenna interference detection and recording system was developed by DLR which is capable to detect the presence of radio interference signals and automatically record a snapshot of raw data. These raw data contain intermediate frequency (IF) signal samples, that we used to analyze the interference event according to a methodology that will be later presented in this paper. The paper also describes the developed measurement system and presents an overview of the results of the campaign.

MEASUREMENT SYSTEM

A simplified block diagram of the measurement system is shown in Fig. 1. The key elements of the system are: a seven element conformal antenna array receiving signals in GPS/Galileo L1/E1 and L5/E5a frequency bands, two analogue radio frequency (RF) front-ends - one for each frequency band -, and a recorder of snapshots containing raw IF signal samples. The recording of the signal snapshots is triggered by an interference detection algorithm. Because of the large amount of recorded data, these snapshots were saved on an external RAID storage with the sufficient capacity. Additionally, a multichannel GNSS receiver prototype developed by DLR was concurrently used with the snapshot recorder (see Fig. 1). A satellite telecommunications link was used for the remote control and monitoring tasks. Both the GNSS conformal antenna array and the Inmarsat terminal antenna were installed above the navigation bridge of the ship (see Fig. 2). A vessel of company Hapag-Lloyd, a large container ship of the Hamburg Express class (366 meters length, beam (width) of 48 meters and a gross tonnage of 142,292 tons), is used as a mobile measurement platform. During the time of the measurements the vessel served a route from Europe to Asia (see Fig. 3), covering different regions and docking in several countries.

The 7-element GNSS antenna array used in the measurement system (see Fig. 1) allows for the characterization of the received signals in the spatial domain. The elements of the array are placed on a hemispherical support, such as to increase the received energy from signals impinging with low elevation angles and hence gain maximum information from signals of all possible receiving directions. The installation of the array on the deck above the navigation bridge of the vessel at a height of almost 50 meters enabled almost all-around view with just very few obstructions.

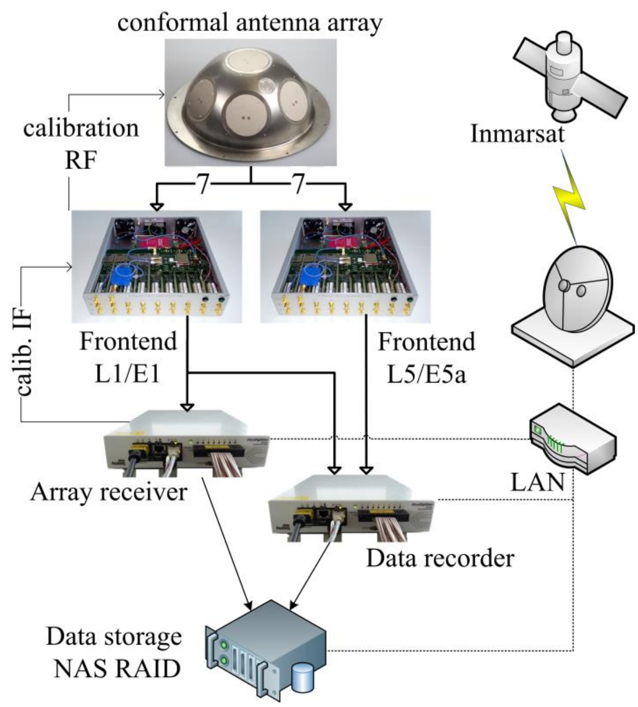


Fig. 1. Measurement system

a) distant view
(photo from vesselfinder.com)

b) close view

Fig. 2. Installed GNSS antenna array

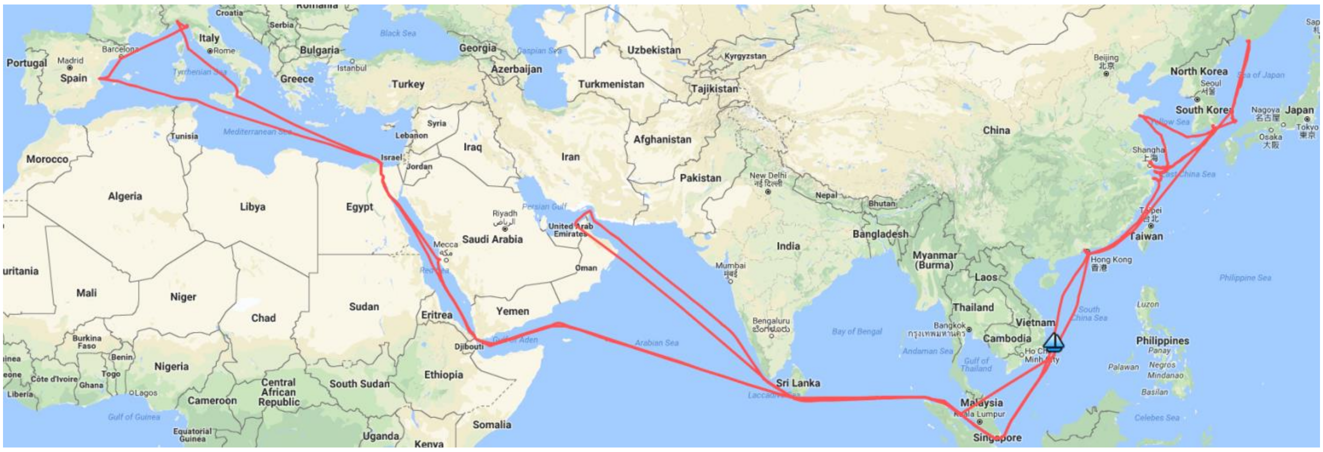


Fig. 3. Route of the container ship during the measurements

Each of the seven RF outputs of the GNSS antenna array is split by a power divider in order to feed two RF front-ends (see Fig. 1). The first front-end performs analogue filtering and down-conversion of the signals falling in the L1/E1 frequency band, while the second front-end performing the same operations for the L5/E5a band. Both front-ends operate with the common intermediate frequency (IF) of 75 MHz. The signal bandwidth at the outputs of the front-ends, defined by the cumulative filtering effect of the entire analog signal path, is approximately 20 MHz in L1/E1 and 24 MHz in L5/E5a. More details about the design of the RF front-ends can be found in [9].

The IF-outputs of the front-ends are concurrently processed by the snapshot recorder and the multichannel GNSS receiver. Both the snapshot recorder and the multichannel receiver are realized by using the same hardware platform. The platform features 16 analog-to-digital converters (ADCs), which is sufficient to sample all 14 IF outputs of front-ends for both L1/E1 and L5/E5a bands (see Fig. 1). The snapshot recorder implementation is based on an example code for a record and playback function provided by the manufacturer. A circular buffer for the IF samples that is realized in the FPGAs is controlled by C++ software running on the CPU of the platform. The control software was designed to detect the presence of interference and trigger recording of snapshots of real-valued IF samples for the analysis in post-processing. A single signal snapshot is defined as a block of 50 ms (160 MB large) or 30 ms (96 MB) containing the signals of all seven array elements of two frequency bands (i.e. L1/E1 and L5/E5a). The sampling rate of the IF samples is 100 Msps which results in the digital IF of 25 MHz. Each signal sample is quantized with 14 bit resolution. The power level of the RF front-end outputs is adjusted in such a way that only the amplitude range of 3-4 bits is used during the quantization process under interference-free conditions, while the full amplitude range of 14 bits is utilized to resolve strong RFI signals without suffering from clipping effects. The recorded signal data are then transferred to a network attached storage (NAS) redundant array of independent disks (RAID) with the capacity of 4 TB.

The GNSS multichannel receiver is a modified version of the demonstrator GALANT developed by DLR [9] that was customized to accommodate 7 array elements, comply with the national export regulations and be able to work autonomously. In this version of the receiver only GPS L1 C/A signals are used for positioning. The post-correlation adaptive beamforming provides some additional resistance to RFI due to the enhancement of GPS signals, however no null-steering for interference mitigation is utilized. The receiver was configured to save the status information of the tracking channels and the Position-Velocity-Time (PVT) solution every 20 seconds. Also, typical observables of a GNSS receiver – ranges, Doppler and C/N0 values of each tracked satellite – have been logged every second.

METHODOLOGY

The real-time detection algorithm is based on the test of the amplitude of the digitized IF samples. Due to the very low power of GNSS signals, it is assumed that under interference-free conditions the outputs of the RF front ends are dominated by the receiver thermal noise and therefore the IF samples follow the Gaussian distribution, i.e. $x[n] \sim N(\mu, \sigma)$. Before its first use, the detection algorithm is manually started in a calibration mode for estimating the parameters of the Gaussian signal model – the mean μ and standard deviation σ – in a controlled interference-free condition. In the detection mode, single trials of every sample $x[n]$ in the snapshot of length N are performed as:

$$\begin{array}{ll} H_0 \text{ (no interference):} & x[n] \in [Thr_-, Thr_+] \\ H_1 \text{ (interference):} & x[n] < Thr_- \text{ or } x[n] > Thr_+ \end{array} \qquad (1)$$

The thresholds Thr_- and Thr_+ are computed with the help of the inverse cumulative distribution function, $\Phi^{-1}(\mu, \sigma, P_{fa})$, of the Gaussian distribution, assuming some target false alarm probability $P_{fa,single}$. For improving the detection performance, the Bernoulli trial strategy is utilized to combine the results of the single trials, i.e. the interference is declared present if at least M out of N single trials deliver H_1 outcomes. The underlying assumption behind the Bernoulli trial is that the single trials are statistically independent. However because of the oversampling effect, the contributions of the receiver thermal noise between adjacent signal samples become timely correlated. In view of this, the parameters M and N were fine-tuned based on the actual performance in practice. The final settings used by the measurement system are $\mathrm{P_{fa,single}} = 10\%$, $\mathrm{N} = 1500$ and $\mathrm{M} = 300$. Additionally in order to benefit from the multiple receive antennas, the RFI detection flag is raised only if interference is detected to be received by at least two array elements (see [10][11][12] for more details). If a snapshot contains interference information, it is saved. In case no interference traces are found, it is discarded or saved for control purposes. Configurable timers are programmed to manage the time intervals between saved snapshots.

The collected snapshots are evaluated in post-processing, with the aim of characterizing and cataloguing the detected interference events. This task is accomplished by concurrently using the IF samples from the RFI snapshots and the observables of the multichannel GNSS receiver. Also the GNSS positioning information is used, when available, to geographically situate the recorded event. For each RFI event, the following metrics are available:

- The estimated received power for each array element and its time evolution. An increase of the received signal power is a strong indication of an RFI event.
- Power spectrum density (PSD) and spectrogram: these metrics help to characterize interference signals in time-frequency domain and identify the number of simultaneously present interference signals.
- C/N0 of the calibration signal: the receiver generates this signal, which is injected into the antenna electronics, for the array calibration purposes. This BPSK-modulated signal on L1 carrier is processed in the receiver as any other GPS impinging signals. In case of strong interference, both signals and the calibration signal are disturbed. However when GNSS signals are blocked, the calibration signal is continuously tracked.
- Eigenvalues of the pre-correlation covariance matrix: In the absence of radio frequency interference, the elements of the spatial pre-correlation covariance matrix are dominated by the noise contribution; hence the spread of the

eigenvalues is small. The presence of a strong interference is manifested by one or more eigenvalues being significantly larger than the rest.

By using the metrics listed above, the analysis of the measurement data is performed according to the following steps:

1) The amplitudes of the IF signal samples in a given snapshot are examined similar to the real-time processing in the data recorder in order to confirm the presence of interference.
2) In parallel the eigenvalues spread is looked into, to verify the actual presence of RFIs in the spatial eigenvalues domain.
3) Also in parallel the C/N0 of the calibration signal is looked into, e.g. to disregard obstruction events.
4) PSD and spectrogram are computed and compared with the ones obtained for an interference-free case.
5) The PVT solution is analyzed in order to assess the impact of the RFI event on the array receiver.

MEASUREMENT RESULTS

In total 78640 snapshots of IF samples containing the data for both L1/E1 and L5/E5a frequency bands have been collected. Fig. 4 shows the distribution of the number of recorded snapshots over the single days of the measurement campaign. While performing the offline analysis, the presence of potential RF interference is typically detected in a portion of the snapshots. Fig. 5 shows how large it the portion of the snapshots with identified interference signals in different days of the measurement campaign. If to check the location of the container ship in those days where the human-made emissions in L1/E1 band are observed more often, it typically turns out that the ship was in these days either in a harbor or in a close vicinity of the land.

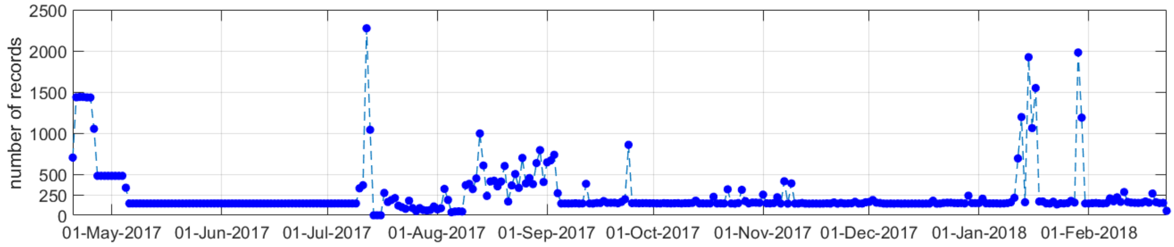


Fig. 4. Number of recorded snapshots per measurement day

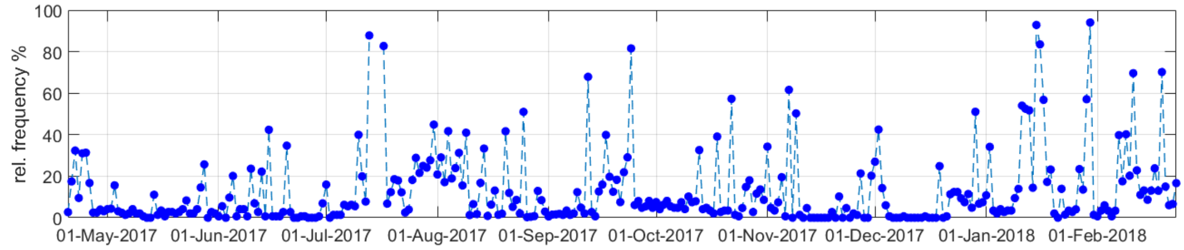


Fig. 5. Relative frequency of snapshots with detected interference in L1/E1 frequency band

The interference effect is strongly determined by the received power of the interfering signals. Therefore in order to assess this effect, the signal samples of each snapshot were used to compute the received power at the IF level and observe its time variation over different snapshots. In order to make this assessment representative for a regular GNSS receiver that uses a single antenna, the variation of the received power is inspected in the signal path of the antenna element 7 that is on the top of the conformal array (see Fig. 1). Fig. 6 and Fig. 7 show the relative variation of the received power in L1/E1 and L5/E5a bands for the entire time of the measurement campaign. The power variations are given with respect to a reference power level that corresponds to interference-free conditions. By setting thresholds on the increase of the received power occurred because of the contribution of interfering signals, the individual RFI events can be identified. The resulting interference impact on the receiver can be then classified in different categories as presented in Table 1. As can be seen in Table 1, in total 331 individual interference events have been identified, with 148 occurrences of strong interference where the received power increased by 5 dB and more. An extremely strong and long-lasting interference was observed in January 2018 (see Fig. 8), that was mainly caused by several CW-like signals. Table 2 presents the results for the duration of the observed interference events. The denial time for GPS L1-C/A is assessed by using the tracking results for the calibration signal. Due to its nature, this signal is not enhanced by the beamforming process performed in the multichannel receiver and therefore can be considered as representative for a regular GPS L1-C/A receiver.

The analysis of the signal situation in L5/E5a band shows that the variations of the received power are, to a very large extent, caused by the pulsed signals of the aviation DME/TACAN system. Since GNSS and DME/TACAN share the same spectrum, the appropriate design of a L5/E5a navigation receiver has to account for this. As can be seen from Fig. 7, the variation the input RF power can be in this situation as high as 30 dB. However, the estimated duty cycle of a digital pulse blanker seldom exceeds 9-10%. Fig. 9 presents an example of the post-processing results for L5/E5a band where the estimated duty cycle reaches the highest observed value of 13.9%. The spikes in the PSD-plot (see Fig. 9a) match the expected positions corresponding to the frequency channels of the ground DME stations.

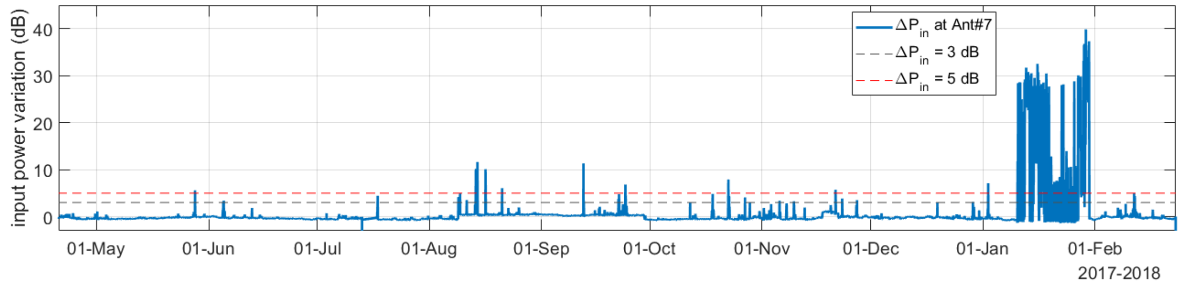


Fig. 6. Variation of received power in L1/E1 band

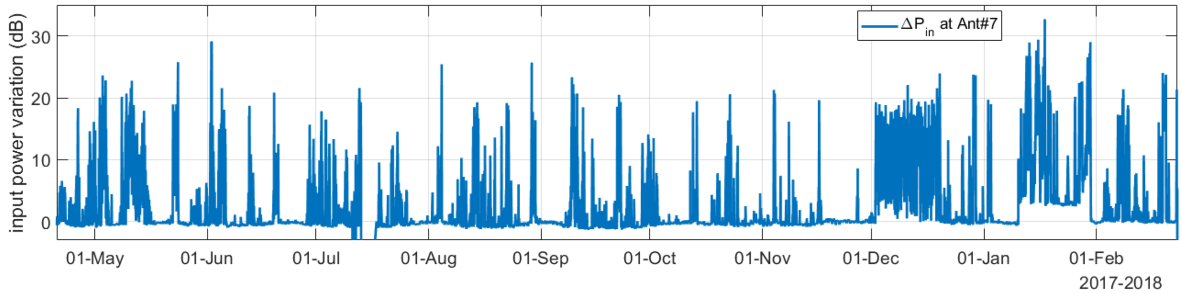


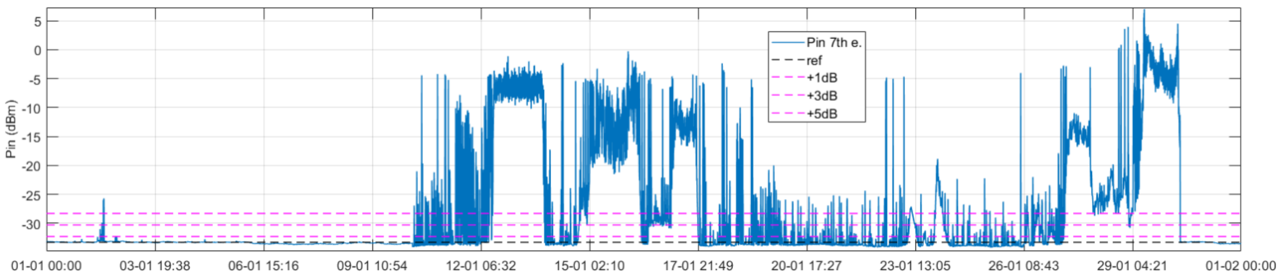
Fig. 7. Variation of received power in L5/E5a band

Table 1. Number of detected interference events in L1/E1 band

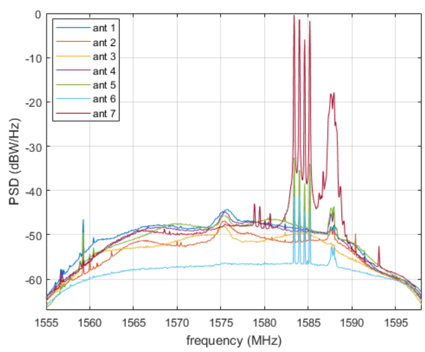
RFI effect	Increase of received power (dB)	Number of RFI events
weak	$\Delta P_{in} \in [1, 3[$	134
medium	$\Delta P_{in} \in [3, 5[$	49
strong	$\Delta P_{in} \geq 5$	148

Table 2. Duration of interference events in L1/E1 band

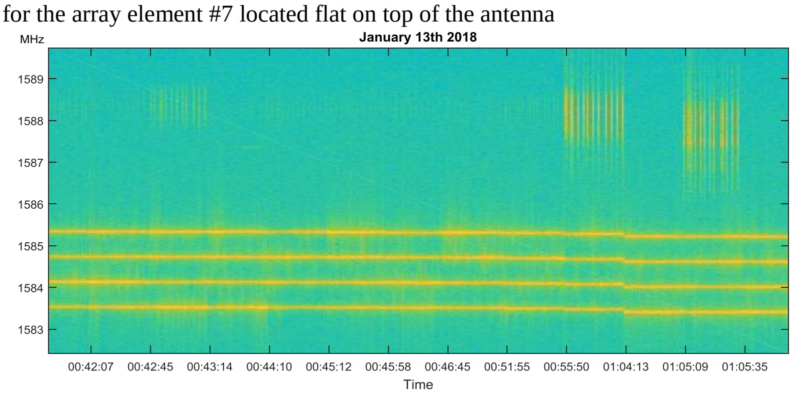
Duration of event (min)	Number of RFI events	Average time of denial of GPS L1 C/A
[0, 5[	205	10 sec
[5, 30[	64	186 sec
[30, 60[	30	9.7 min
≥60	32	218 min



a) ADC input power for the array element #7 located flat on top of the antenna

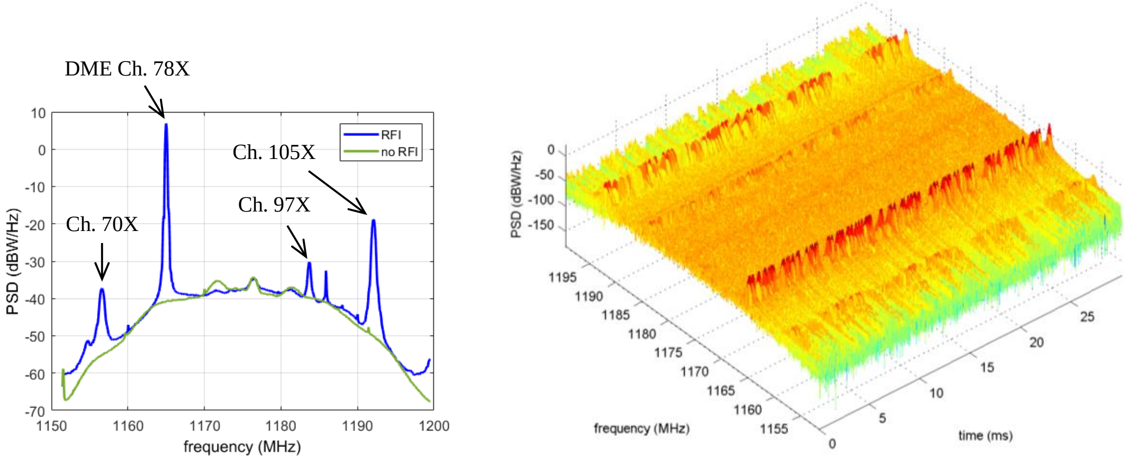


b) PSD on 13-Jan-2018, 00:55h UTC



c) spectrogram, 13-Jan-2018

Fig. 8. The most severe interference observed in L1/E1 band



a) power spectrum density
b) spectrogram

Fig. 9. A representative example of results for L5/E5a band:
10-Sept-2017, estimated duty cycle of 13.9%

CONCLUSIONS

An international maritime measurement campaign has been performed from April 2017 until February 2018 in order to detect and record snapshots of IF samples containing representative RFI signals. The collected measurement data allows us to take a deeper look at the interference situation in GPS/Galileo L1/E1 and L5/E5a frequency bands for the maritime domain. A short overview of the results of the post-processing and analysis of the measurements has been presented. The presented results indicate that a big number of RFI events could be observed during the measurement campaign, some of them with considerable power values. Though not claiming to be an exhaustive analysis of all possible interference events in the maritime domain, the presented work shows however the first world-spanning analysis. The authors believe this information will be a valuable input for the development of corresponding interference threat models for the maritime GNSS applications and countermeasures.

ACKNOWLEDGEMENTS

The reported results has been obtained in the frame of the siNafa project (03SX411C) funded by the German Federal Ministry for Economic Affairs and Energy. This support is greatly acknowledged. The authors also gratefully acknowledge the support of the Hapag Lloyd Company that made the maritime measurement campaign on one of their container ships possible.

REFERENCES

[1] A. Parkins, A. Grant, and P. Cross, "The Impact of New Signals on Precise Marine Navigation - Initial Results from an Experiment in Harwich Harbour." Proc. of Navigation Annual Conference and Exhibition of Royal Institute of Navigation, 28-30 Oct. 2008, London, UK, pp. 486–499, 2008.

[2] A. Grant, P. Williams, N. Ward, and S. Basker, "GPS Jamming and the Impact on Maritime Navigation," *J. Navig.*, vol. 62, no. 2, pp. 173–187, 2009.

[3] IMO Sub-Committee on Safety of Navigation, "Development of an e-Navigation strategy implementation plan." 2011.

[4] IALA, "IALA Recommendation R-129 on GNSS vulnerability and mitigation measures." pp. 1–19, 2008.

[5] "Assessment of Radio Frequency Interference Relevant to the GNSS (RTCA/DO-235A)," RTCA, Inc., 2002.

[6] M. Dumville, "Initial Findings from the STRIKE3 GNSS Interference Monitoring Network", Presented on the 21st Meeting of Space Based PNT Advisory Board, 16-17 May 2018, Baltimore, MD, USA.

[7] J. R. Clynch, A. A. Parker, R. W. Adler, and W. R. Vincent, "System challenge—The hunt for RFI—Unjamming a Coast Harbor," *GPS World*, pp. 16–22, 2003.

[8] U.S. Federal Bureau of Investigation, "Cargo Thieves Use GPS jammers to Mask GPS Trackers," Private Industry Notification PIN #: 141002-001, 2 October 2014.

[9] M. V. T. Heckler, M. Cuntz, A. Konovaltsev, L. A. Greda, A. Dreher, and M. Meurer, "Development of Robust Safety-of-Life Navigation Receivers," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 4, pp. 998–1005, Apr. 2011.

[10] A. Konovaltsev et al, "Interference Detection and Characterization with an Array based GNSS Receiver using Conformal Antennas in Maritime Environments", *Proc. of ION GNSS+ 2017*, Portland, OR, USA, Sept. 2017, pp. 2795-2811.

[11] E. Pérez Marcos et al, "Interference Awareness and Characterization for GNSS Maritime Applications", *Proc. of IEEE/ION PLANS 2018*, Monterey, CA, USA, April 2018, pp. 908-919.

[12] E. Pérez Marcos et al, "Interference and Spoofing Detection for GNSS Maritime Applications using Direction of Arrival and Conformal Antenna Array", *Proc. of ION GNSS+ 2018*, Miami, FL, USA, Sept. 2018, pp. 2907-2922.